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Investigation on the feasibility and enhancement methods of wind power utilization in high-rise buildings of Hong Kong

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Abstract

This paper reports the investigation results of wind power application in buildings. It is found that the concentration effect of buildings and the heights of buildings could enhance wind power utilization by increasing the wind speed by 1.5–2× and wind power density by 3–8× under the given simulation conditions. The wind aerodynamics and wind flows over the buildings are investigated based on local meteorological data and local high-rise building characteristics. This paper concludes that wind power utilization in high-rise buildings in Hong Kong is feasible theoretically, and some effective enhancement methods are proposed based on the simulation results, such as making full use of the heights of buildings and the concentration effect of buildings, and choosing optimal shape of building roof. However, to receive the highest potential wind energy resource and avoid turbulent areas, the tool of Computational Fluid Dynamics (CFD) has to be used to model the annual wind flows over buildings to help analyze, locate, and design wind turbines in and around buildings.
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Keywords: Wind power utilization; Buildings; Concentration effect; Turbulence; Wind turbines

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1. Introduction

Renewable energy technologies can bring social, environmental and economic benefits to our community. Our energy

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Nomenclature

C_μ	constant
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants
G_k	the generation of turbulence kinetic energy due to the mean velocity gradients
G_b	the generation of turbulence kinetic energy due to buoyancy
u_{i}	mean velocity components along x, y and z axes
S_{k}, S_ε	user-defined source terms
Y_{M}	the contribution of the fluctuating dilatation in compressible turbulence to overall dissipation rate

Greek symbols

μ	air viscosity
μ_{t}	turbulent (or eddy) viscosity
ρ	fluid density
σ_k	the turbulent Prandtl number for k
σ_ε	the turbulent Prandtl number for ε

strategy should seek to maximise our city's own generation of renewable energy and aim to minimise the impacts on health and on local and global environment for meeting the essential energy needs of all those living and working in our city [1]. One of the renewable energy technologies, and its uses are well suited to urban environments and considered particularly appropriate for urban buildings is wind power generation. Wind power in buildings is seen as an opportunity in urban areas [2–5], but the built environment has relatively lower average wind speeds and higher turbulence levels. However, the disturbed flows around buildings can locally increase wind speeds, and the energy yields may be increased compared to open sites. As the energy yields of wind turbines have the cubic relationship with wind velocity, the wind speed increase due to the effect of surrounding buildings could make wind turbines in favor of wind.

Wind energy in buildings, with turbines being mounted on or integrated into buildings, involves many different challenges for stand-alone wind energy systems. Wind turbines located at the high wind speed zones in buildings are called Building Augmented Wind Turbines (BAWT), and the wind turbine makes use of buildings as a concentrator of wind. So far, the existing utilization types in urban areas are: building mounted (small-scale wind turbines), including Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (HAWT); and building integrated turbines, including Patented Wind Energy System [6] and other concepts, such as ''Bluff Body'' Concept (New London tower to have its own wind farm of the 147 m high tower featuring three 9 m diameter wind turbines to produce electricity to light the entire building [4]), and ''Diffuser'' Concept [7] (such as the Bahrain World Trade Center with its intuitive wind use of facade engineering in Dubai, as demonstrated in Fig. 1a). Three wind turbine blades have been successfully installed on the Bahrain World Trade Center, a twin skyscraper complex. This is the first time that a commercial development has integrated large-scale wind turbines within its design to harness the power of the wind. The three massive turbines, measuring 29 m in diameter, are supported by bridges spanning between the complexes two towers. Through its positioning and the unique aerodynamic design of the towers, the prevailing on-shore Gulf breeze is funnelled into the path of the turbines, helping to create power generation efficiency. The rebuilding plans of New York World Trade Center [8] also include plans to incorporate wind turbines that will generate 20% of the building's electrical power needs, as featured in Fig. 2b. The Freedom Tower will be the world's tallest building and will incorporate state-of-the-art safety systems that far exceed New York City's building code requirements. If built as planned, the Freedom Tower's use of wind turbines would be the world's another large-scale integration of wind turbines into a building.

Meanwhile, turbines being mounted on or integrated into buildings involves many different challenges to stand-alone wind systems. So far, there are some existing building-integrated projects and upcoming projects in the near future, but few researches have been conducted to investigate the wind flows over the buildings for wind power utilization purpose, and no research was performed to compare the advantages of building-integrated wind systems with remote stand-alone wind systems [2].

To find the feasibility and wind enhancement methods for wind power utilization, investigation on wind aerodynamics and wind flows over buildings in urban areas is crucial. Computational wind engineering (CWE) has been developed recently to evaluate the interaction between wind and buildings numerically, and the Computational Fluid Dynamics (CFD) can be used to model wind flows over buildings to help analyze, locate, and design turbines in and around buildings. Turbulence modeling and meshing are the two major issues considered to be important for successful application of computational fluid dynamics to environmental flows [9]. Meroney etc. [10] compared the standard k–ε, the non-linear k–ε (RGN k–ε) and the Reynolds-stress RSM turbulence closure approximations for modeling the flows and dispersion of gases emitted by sources located near different building shapes. As a conclusion, the RSM turbulence models produced more realistic results than the k–ε or RGN models, and the inlet conditions and boundary conditions should be specified to the best information available for fluid modeling simulation. There are many researchers working on the numerical modeling and meshing the flow domain of wind flows [11,12], but few researches are conducted to investigate the wind flows over buildings for wind power utilization [13].

In Hong Kong, studies in wind power mainly focus on wind power assessment for rural areas [14–18], wind speed estimation [19] and local meteorological data for wind power utilization [20]. In commercial market, there are two single wind turbine projects (onshore) being constructed or running, and potential offshore wind farms are on the road [21]. A 1 kW horizontal-axis small wind turbine and a 1.5 kW vertical-axis small wind turbine have been installed on the roof of the EMSD Headquarters Building [22], as shown in Fig. 2, for demonstration purpose and

(a)

(b)

Fig. 1. Building-integrated wind turbines (a) on Bahrain World Trade Center of Dubai [7], and (b) planned on the rebuilt New York World Trade Center [8].

for gathering experience on roof-top application of small wind turbines. The small wind turbines are grid-connected, using small wall-mounted grid-tie inverters. However, no study on BAWT is conducted yet although Hong Kong is characterized by high wind potential and densely high-rise buildings.

Therefore, it is important to evaluate the interaction between wind and buildings numerically and to model wind flows over buildings to help analyze, locate, and design BAWT based on local wind meteorological data and local urban terrain characteristics for assessing and improving local urban wind power utilization. In addition, this could also be of interest to city planners, designers, and builders as wind climate in urban areas and its ramifications are together with urban environmental, structural and architectural engineering practices. This paper aims to investigate the wind aerodynamics and wind flows over high-rise buildings for wind power utilization based on local meteorological data and local urban building characteristics, and to address the strategies on how to develop

(a) (b)

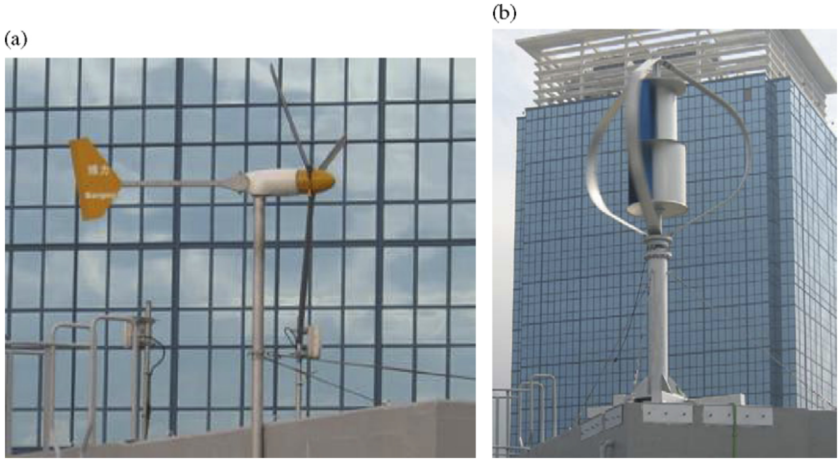

Fig. 2. (a) 1 kW horizontal-axis, and (b) 1.5 kW vertical-axis small wind turbines on the roof of EMSD headquarters building of Hong Kong.

wind power in local urban areas more effectively, such as the optimal roof shapes (including its orientation) in favor of wind power application and the utilization of the concentration effect of buildings.

2. Numerical modeling

Computational wind engineering (CWE) has been developed recently to evaluate the interaction between wind and buildings numerically, and Computational Fluid Dynamics (CFD) can be used to model wind flows over buildings to help analyze and locate turbines in and around buildings.

2.1. Mathematical modeling

Turbulence modeling and meshing are the two major issues considered to be important for successful application of computational fluid dynamics to environmental flows. The FLUENT provides several turbulence models, and the standard k–ε model is applied in this paper. The turbulence kinetic energy, k, and its rate of dissipation, ε, are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_{\mathrm{M}} + S_{\mathrm{k}} \tag{1}$$

and

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - \rho\varepsilon - C_{2\varepsilon}\rho\frac{\varepsilon}{k} + S_\varepsilon \tag{2}$$

For the turbulent viscosity,

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{3}$$

2.2. Geometry scenarios

Based on local building characteristics, three scenarios are chosen to investigate the wind conditions between two buildings in terms of building heights and the distances, and to study the wind flows over the building roof considering shapes and building heights [12], as listed in Table 1.

Scenario A is to find out the effect of different building distances on the wind flows between buildings. Three cases are simulated with the distances of 10 m (Case 1), 15 m (Case 2, see Fig. 3) and 20 m (Case 3), respectively. The dimension of the two identical buildings is 25 m × 70 m (h) × 25 m.

Scenario B is to find out the effect of building heights on the wind velocity and wind flows between two buildings. Two identical buildings with dimension of 25 m × 140 m (h) × 25 m are established to make a comparison with Case 2 in Scenario A.

Scenario C is to study the relationships between wind flows over building roof and the building heights, and to investigate the influence of the roof shapes on wind velocity and wind flows over the roof. As shown in Fig. 4a, Building 1 (the left one) is established with dimensions of 25 m × 70 m × 25 m, Building 2 (the middle one) is established with dimension 25 m × 140 m × 25 m and building 3 (the right one) is 25 m × 210 m × 25 m. In addition, Case 2, as shown in Fig. 4b, is to demonstrate the influence of the roof shapes (Catercorner flat roof) on the wind flows.

2.3. Weather data input

The weather data, including wind velocity, wind direction and temperature, were obtained from the Hong Kong Observatory. In this study, the mean wind speed and temperature are chosen as inputs based on local research [16]. The simulated wind flows vertically through the buildings in Scenario A and B, and the wind direction is from Building 1 to Building 3 in Scenario C. For example, the data input for Scenario A is as follows:

Temperature: 296.1 K
Wind speed: Wind speeds for inlet 1 to inlet 6 in Scenario A are:

Boundary name	Height (m)	Wind speed (ms^{-1})
Inlet 1 (the bottom one)	0–10	6.027
Inlet 2	10–30	7.051
Inlet 3	30–50	7.585
Inlet 4	50–70	7.96
Inlet 5	70–90	8.25
Inlet 6 (the top one)	90–120	8.5957

3. Results and discussion

With the given data input and model constants [12], Scenarios A and B give the wind conditions between two buildings considering different building distances and building heights while Scenario C focuses on the wind flows over the roof of the buildings in terms of different buildings heights and different roof shapes.

3.1. Scenario A: wind flows between buildings with different building distances

Three cases with the building distances of 10 m, 15 m and 20 m are simulated and analyzed, as demonstrated in Figs. 5 and 7.

3.1.1. Increase of wind velocity and wind power density between buildings

The wind velocity in the vertical channel of two buildings increases sharply from the inlet boundary, reaches the highest at the narrowest point of the two buildings and then decreases to

Table 1
Three geometry scenarios

Items		Building description	Building distance (m)	Remarks
Scenario A	Case 1	Two identical buildings: 25 m × 70 m (h) × 25 m	10	
	Case 2		15	See Fig. 3
	Case 3		20	
Scenario B	Case 1	Two identical buildings 25 m × 70 m (h) × 25 m	15	Scenario A: Case 2
	Case 2	Two identical buildings 25 m × 140 m (h) × 25 m		
Scenario C	Case 1	Building 1 25 m × 70 m (h) × 25 m	25	See Fig. 4(a)
	Case 2	Building 2 25 m × 140 m (h) × 25 m		See Fig. 4(b) with catercorner flat roofs
		Building 3 25 m × 210 m (h) × 25 m		

the outflow boundary (see Fig. 5). The highest wind speed exists at the middle level of the building height, and there is also wind increase near the side walls of the buildings.

For the three cases, under the given simulation conditions, the highest wind velocity between buildings could reach around 15 m/s, which means around 8× increase of wind power density due to the cubic relationship between wind speed and wind power density, as demonstrated in Fig. 6. The power density over 2000 W/m^2 is much higher than the standards of the highest wind power class of 7 (>800 W/m^2 at 50 m high) defined by DOE [23]. The results prove that the concentration effect between buildings can increase wind power generation significantly. Although the integration of large-scale wind turbines is far too expensive to put into practice at the moment, the yields of the

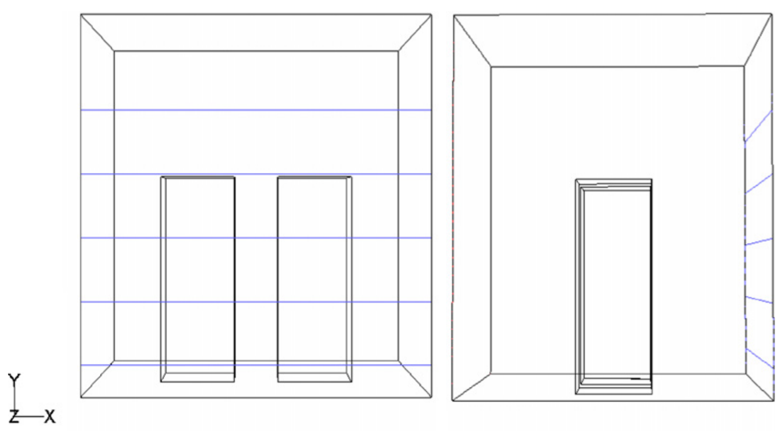

Fig. 3. Geometry of Scenario A: Case 2 (building distance: 15 m).

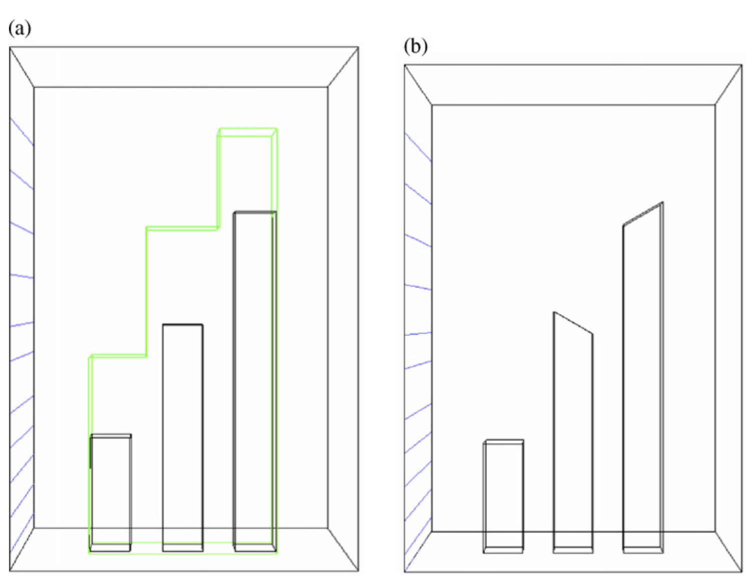

Fig. 4. (a) Geometry of Scenario C: Case 1, and (b) Geometry of Scenario C: Case 2.

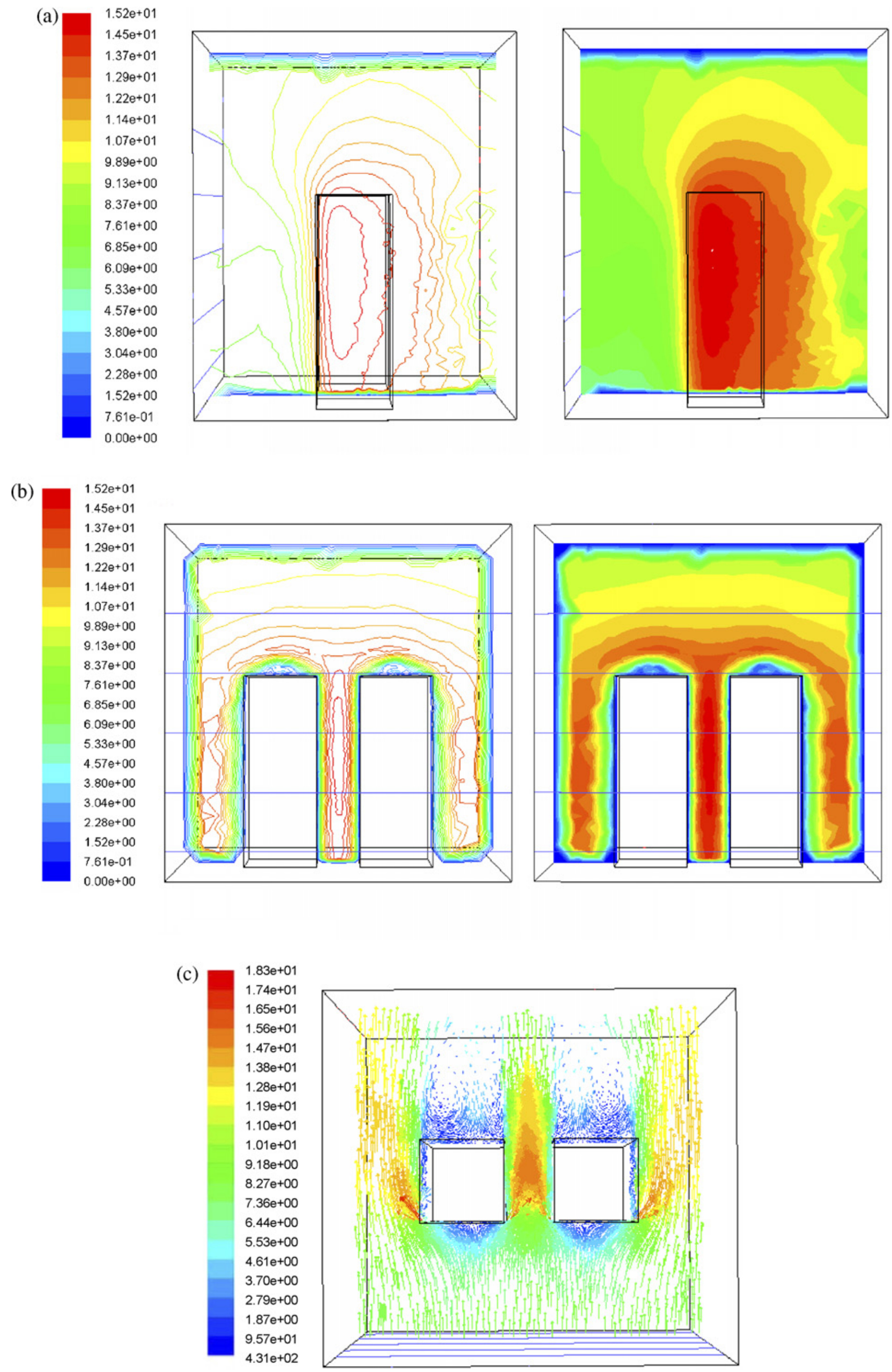

Fig. 5. Contours of velocity magnitude (m/s) of Scenario A: Case 2: (a) side view, (b) front view, and (c) top view.

wind turbines could be increased by a few times once optimal location is selected, which will offset the high initial cost.

Amongst three cases, Case 1 has the highest velocity of 15.6 m/s due to the shortest building distance. The distances between buildings affect the increase of the wind speeds, and theoretically, higher wind velocity exists with shorter building distance. However, other considerations need to be taken as well, such as building design standards, the dimension of wind turbines, the layer thickness of turbulent flows, etc.

3.1.2. Turbulence layer and location

Turbulence is another factor concerned in wind power utilization as turbulence should be avoided for the installation and operation of wind turbines. There are turbulent flows over the surfaces of the buildings and the thickness of the turbulence layers is thin, about 3 m apart from the building surfaces for all the three cases (see Fig. 7). In these cases, the wind turbines should be installed 3 m away from the buildings to receive higher wind speed and avoid turbulence. Sufficient distance

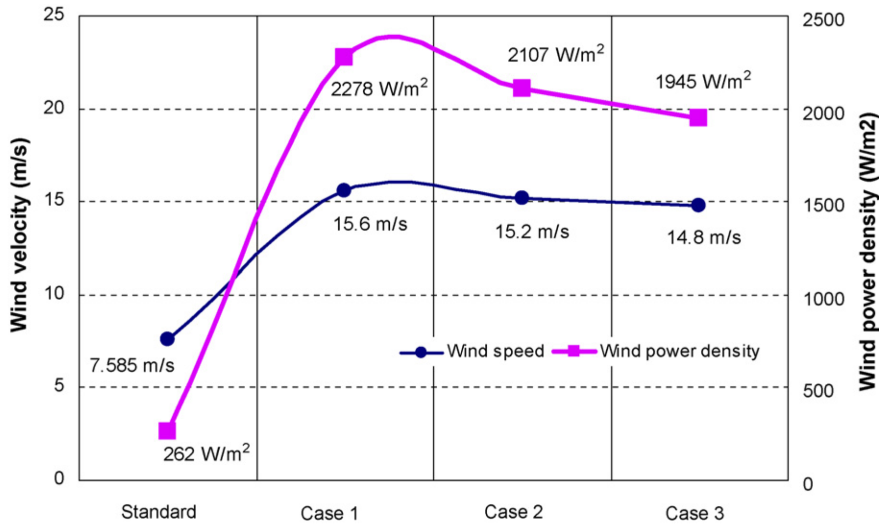

Fig. 6. Comparisons between the standard input and the highest wind speed & wind power density in Scenario A.

between buildings is required for different diameters of wind turbines.

Turbulence mainly happens over the roof, the back sides and the side walls of the buildings. Fig. 7a demonstrates the turbulence over the building roofs and the side walls for Case 2 while Fig. 7b gives the simulation results for the back sides of the buildings for Case 2. The high magnitudes of turbulence bring disadvantages for the operation of wind turbines. To avoid

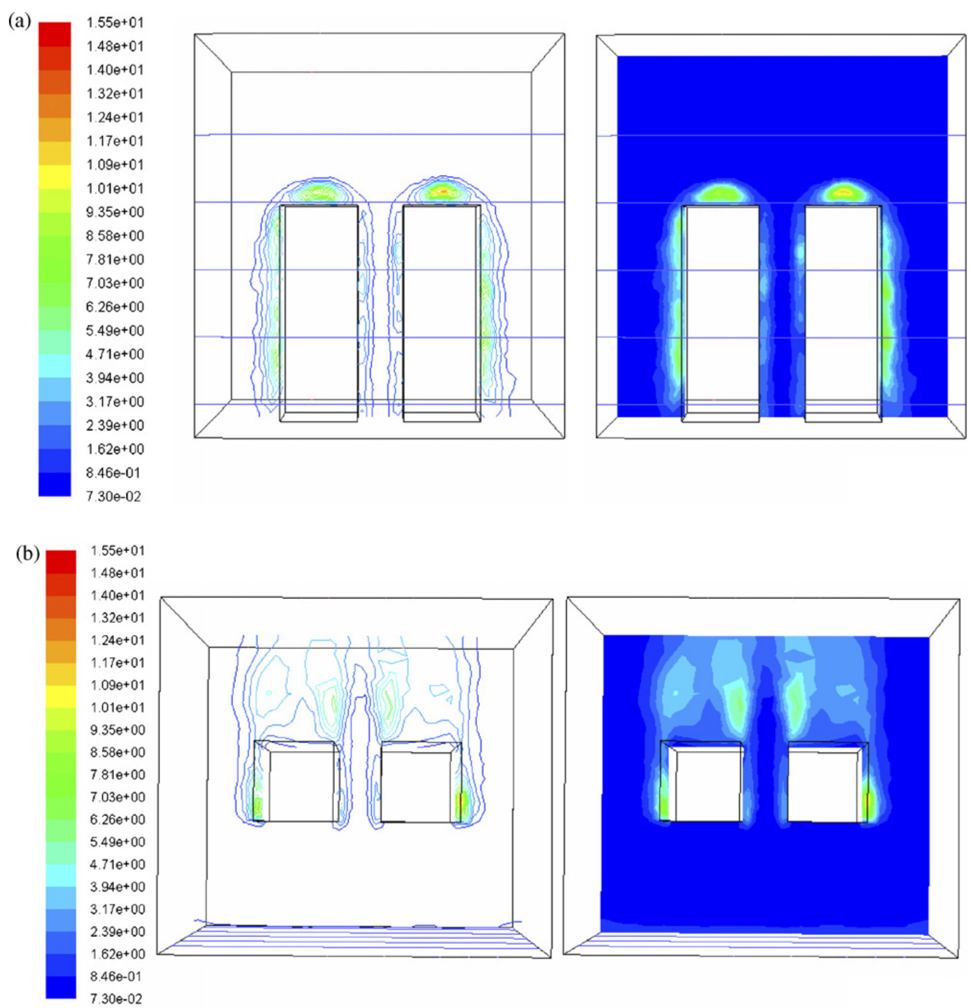

Fig. 7. Contours of turbulence magnitude (m^2/s^2) of Scenario A: Case 2: (a) front view and (b) top view.

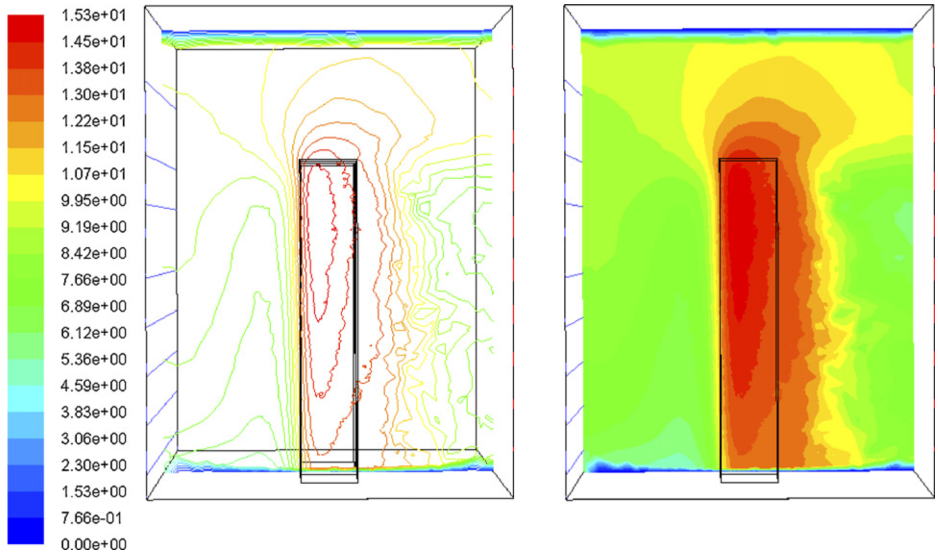

Fig. 8. Contours of velocity magnitude (m/s) of Scenario B: Case 2 (side view).

the turbulence, generally, wind turbines can be installed above 10 m over the roof and 6 m from the side walls under the given wind conditions. In a word, due to existing obstacles, such as buildings, turbulent flows occur over the roof and on the back sides and side walls of buildings. To receive higher wind speeds and avoid turbulence, simulations should be conducted to find out the most favorite locations for the installation of wind turbines. Meanwhile, a detailed investigation should be conducted because short term turbulence could be generally accepted [24], and simulations for observing the wind circumstances during a day, a month, a season or a year should be carried out to find the occurrences and impacts of such turbulence.

3.2. Scenario B: wind flows over two buildings of different heights

To investigate the wind flow patterns between two buildings with different heights, Scenario B with two cases of building heights of 70 m (Case 1) and 140 m (Case 2) are studied, as shown in Figs. 8 and 9.

3.2.1. The influence of the building heights on the wind flows

The wind flow patterns are similar for the two cases, and the highest wind speeds are both around 15.2 m/s (see Figs. 5 and 8). However, the occurrence positions of the highest speed are

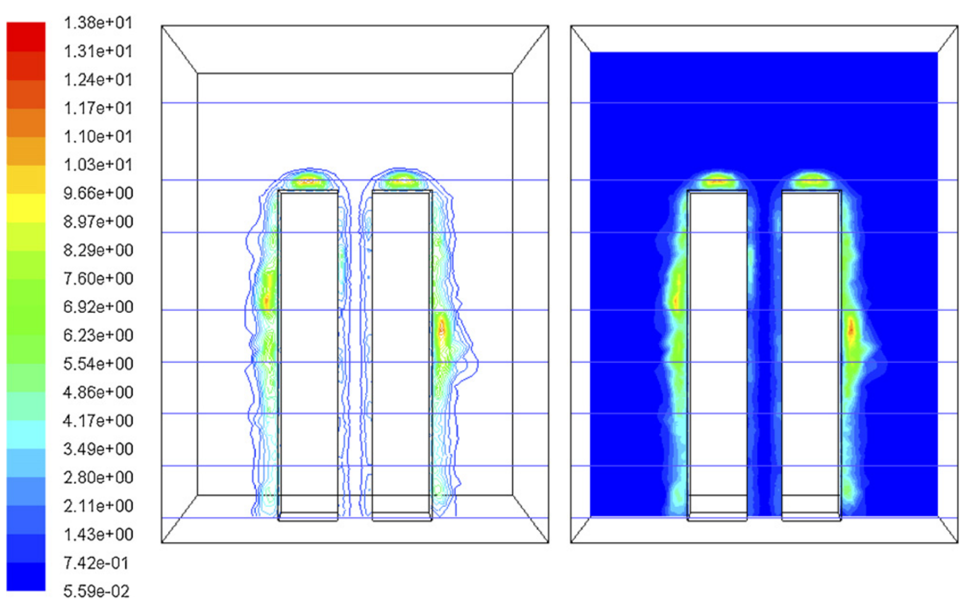

Fig. 9. Contours of turbulence magnitude (m^2/s^2) of Scenario B: Case 2 (front view).

Table 2
The maximum thickness of turbulence layer

Items (m)	Scenario B Case 1	Scenario B Case 2
Away from the wall: between buildings	3	3.75
Away from the single side wall	7.4	11
Away from the roof	6.25	15.6

different for the two cases. The occurrence of the highest velocity for case 1 starts relatively lower from 17 m (1/4 of the building height of 70 m) above the ground to 70 m, and for case 2 relatively higher from 70 m (1/2 of the building height of 140 m) above the ground to the building height. It concludes that the building heights have little effects on the wind speed increase between high-rise buildings, but affect the favorite position level for wind energy utilization between high-rise buildings. For the wind flows between two buildings, the building heights affect the occurrence positions of the highest wind velocity. For tall buildings, the position favorable for wind power utilization is relatively higher.

3.2.2. Turbulence layer and location

The thickness of turbulence layer for Case 2 is around 3.75 m apart from the walls between buildings (see Fig. 9), a little bit higher compared with Case 1 (3 m). Therefore, under the given wind conditions, to avoid turbulence, wind turbines should be installed 7.4 m higher above the roof for Case 1 and 11 m higher above the roof for Case 2, as listed in Table 2. The maximum thickness of turbulence layer occurs in the areas over the middle part of the roof. Over the edge part of the roof, the turbulence layer is thin. That's the reason why the roof-mounted wind turbines should be installed over the edge area, as shown in Fig. 2. For higher buildings, the thickness of turbulence layer over the roof increases, and the turbulence layers at the side walls in Case 2 are also relatively thicker than the layers in Case 1. The maximum thickness is about 6.25 m apart from the side walls for Case 1 and about 15.6 m apart from the side wall for Case 2. Fig. 9 also shows that the location with the thickest turbulence layer for the side wall is at the middle level of the building, and the thickness of turbulence layer are different at different levels. To avoid turbulence, simulations should be conducted to find out the optimal locations for the installation of wind turbines in favor of wind.

3.3. Scenario C: wind flows over the roof

In this Scenario, wind flow conditions over the roof are investigated specifically. The influences of building heights and different roof shapes on the wind flows over the roof are studied.

3.3.1. Scenario C.1: influence of building heights

Three buildings are chosen with the height of 70 m for Building 1 (the left one), 140 m for Building 2 (the middle one) and 210 m for Building 3 (the right one). Wind flows from the left inlet boundary to the right outflow boundary.

Obviously, higher wind speeds exist over the tallest building. Fig. 10 demonstrates that the wind speeds (from 9.51 to 12.7 ms^{-1}) over the roof of Building 3 are much higher than those of Building 1 and Building 2. There are two reasons for the increase: the wind speed increase with the height, and the concentration effect of the buildings. The patterns of wind flows over different flat roofs are similar. Meanwhile, the roof of the taller building is suitable for wind power utilization if the construction design allows. In this case, the wind speed could increase by around 2× (compared with the ground wind speed) and almost 1.5× (compared with the wind speed at same height in open area), which means 8× or 3–4× higher of wind power generation yield theoretically. Thus, using wind power effectively in buildings could be feasible and economical in terms of the investigation.

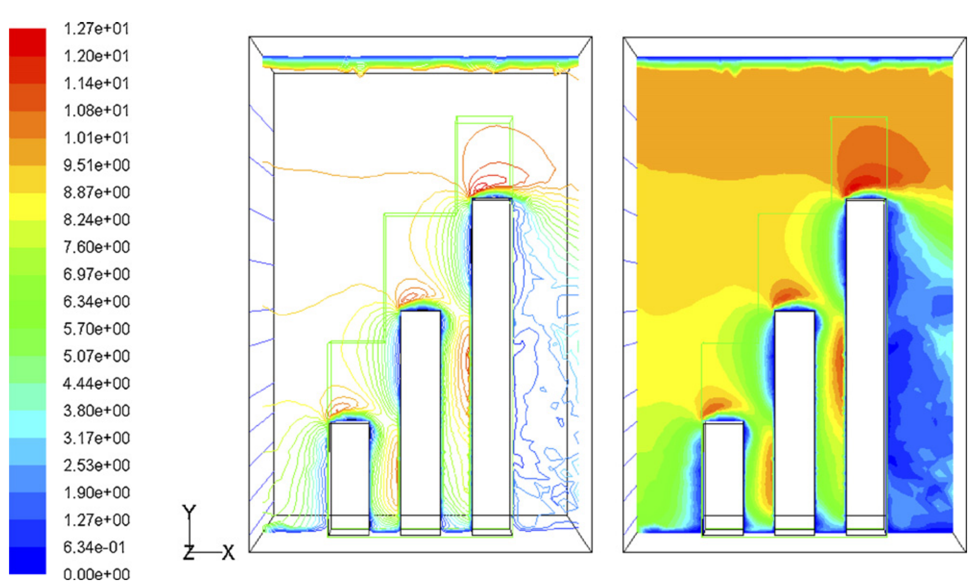

Fig. 10. Contours of velocity magnitude (m/s) of Scenario C.1.

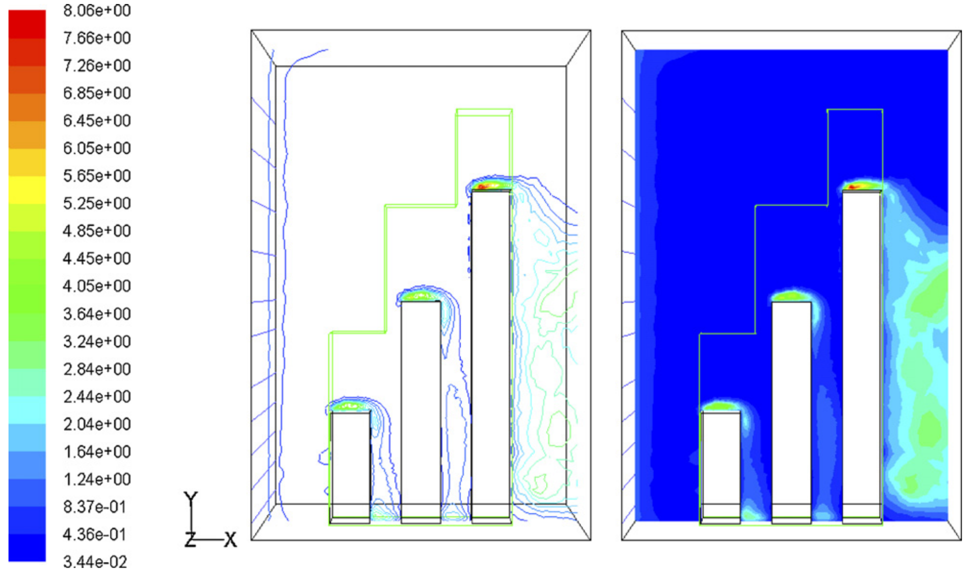

Fig. 11. Contours of turbulence magnitude (m^2/s^2) of Scenario C1.

Meanwhile, there are turbulent layers over the three building roofs, as shown in Fig. 11. The thickness of the turbulence layers is generally about 12 m over the roofs. The turbulence is severe over the higher roof. To avoid the turbulence, wind turbines should be installed and operate higher than 12 m above the roofs under the given weather conditions.

3.3.2. Scenario C.2: influence of roof shapes

Three different building roof shapes are chosen for the study, including flat and catercorner flat roofs. Under the given weather conditions, the highest wind speed is found over the roof of Building 2 instead of Building 3. In Scenario C.1, the roof of Building 3 results in the highest wind velocity due to its height. However, in Scenario C.2, the roof of Building 2 results in the highest wind velocity due to the roof shape. As shown in Fig. 12, the wind speeds vary from 10.1 m/s to 12.7 m/s over the roof of Building 2. The occurrence location of the highest wind speed is also demonstrated for three buildings in the figure. For example, the highest wind velocity over Building 3 occurs over the sharp end corner and afterwards where the turbine installation is difficult.

Compared with the horizontal flat roofs, there is larger turbulent area over the roof of Building 2 than the ones of Building 1 and Building 3 (see Fig. 13). There is almost no turbulent layer over the roof of Building 3 and the inclined slope is facing the wind direction. Although the roof shape of Building 2 can enhance the wind power utilization, it also results in larger turbulent space. Avoiding the turbulent layer but receiving higher speed wind requires the simulation investigation for the optimal location for wind power utilization.

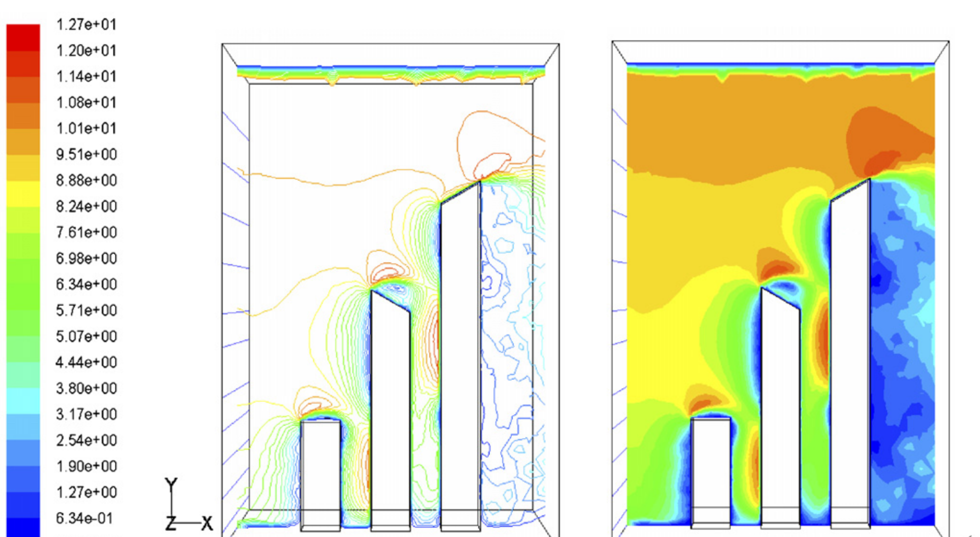

Fig. 12. Contours of velocity magnitude (m/s) over the roof of buildings 1, 2 and 3 of Scenario C2.

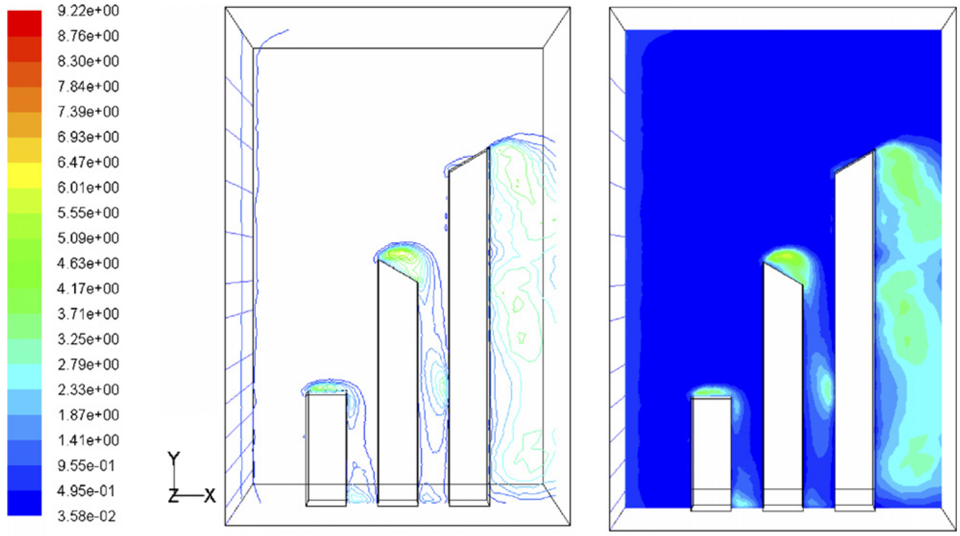

Fig. 13. Contours of turbulence magnitude (m^2/s^2) of Scenario C2.

The optimal installation location of wind turbine could be affected significantly by the roof shape. Roof shapes affect the pattern of wind flows over the roof for example, inclined flat roof (facing wind direction) results in much higher wind speed but also causes a thicker and larger area of turbulence. This implication allows us to integrate the innovative roof design for new building to enhance the wind power utilization in the new building design. The integration between wind turbines and building design could offer the new opportunity of wind power utilizations in cities. For different wind conditions and different dimensions of roof with different building heights, the thickness of turbulence layer and the changing of wind speed could be different, and annual dynamic simulation investigations should be conducted for the application.

4. Conclusions

This paper reports an investigation result of the feasibility of wind power utilization in local urban areas and find out how to develop wind power in the built environment more effectively. By investigating the wind aerodynamics and wind flows over the buildings based on local meteorological data and local building characteristics, the concentration effect of buildings and the heights of buildings could enhance wind power utilization by increasing the wind power density by 3–8× under the given simulation conditions. Computational Fluid Dynamics (CFD) should be used to model annual wind flows over buildings to help analyze, locate, and design turbines in and around buildings for both receiving higher wind speed and avoiding the turbulence layer. For different wind conditions and different dimensions of roof with different building heights, the thickness of turbulence layer and the changing of wind speed could be different, and annual dynamic simulation investigations should be conducted for the specific application.

This paper also addresses the strategies on how to develop wind power in cities more effectively, and proposes the optimal flat roof shape (including its orientation) and building distance in favor of wind power application. Further study on other utilization of the concentration effect of buildings, such as different aerodynamic building concentrators and enhanced wind energy buildings (such as pressure expanding tunnel building, column building, wind barrier building, etc.), and other optimal shapes of building roof (such as concave arc and convex arc, hemisphere, fastigium, etc.), is recommended.

Acknowledgements

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